

The Daya Bay Experiment

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for
The Daya Bay Collaboration

P5 Review, Fermilab, April 18, 2006

θ_{13} : The Last Unknown Neutrino Mixing Angle

U_{MNSP} Matrix

Maki, Nakagawa, Sakata, Pontecorvo

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ -0.4 & 0.6 & 0.7 \\ 0.4 & -0.6 & 0.7 \end{pmatrix} ?$$

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric, accelerator}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{reactor, accelerator}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{SNO, solar SK, KamLAND}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{\text{O}\nu\beta\beta}$$

atmospheric,
accelerator

$\theta_{23} = \sim 45^\circ$

reactor,
accelerator

$\theta_{13} = ?$

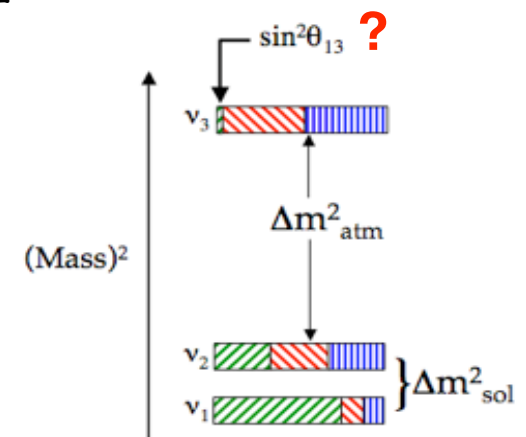
SNO, solar SK,
KamLAND

$\theta_{12} \sim 32^\circ$

$\text{O}\nu\beta\beta$

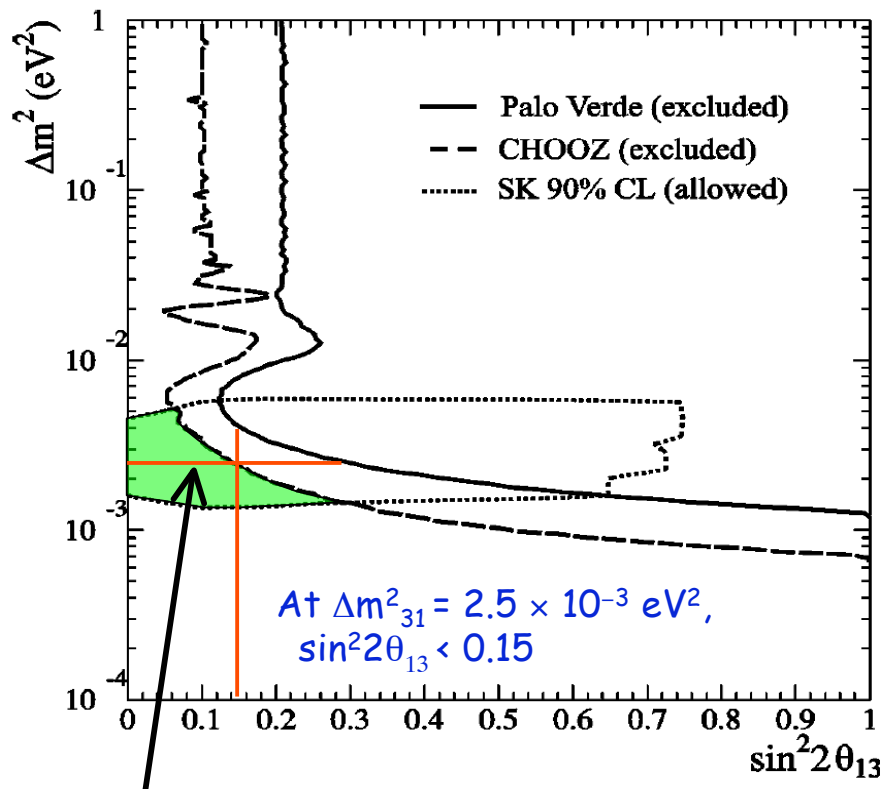
- What is ν_e fraction of ν_3 ?
- U_{e3} is the gateway to CP violation in neutrino sector:

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \propto \sin(2\theta_{12})\sin(2\theta_{23})\cos^2(\theta_{13})\sin(2\theta_{13})\sin\delta$$



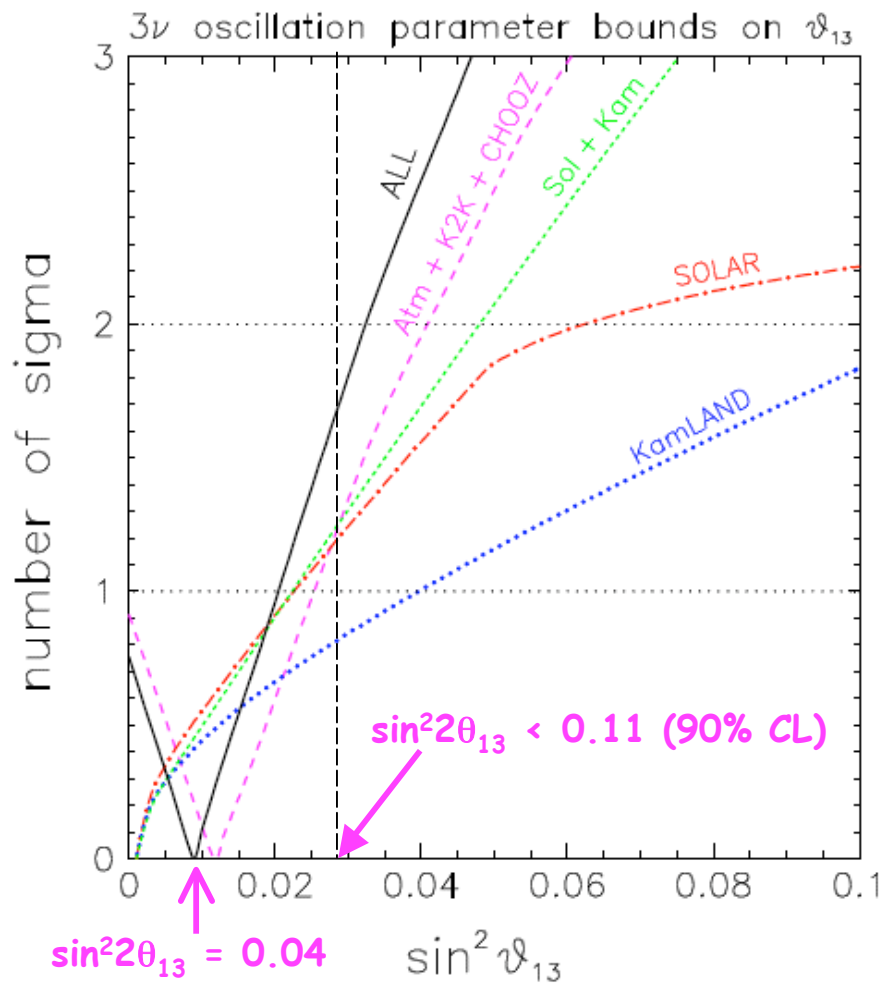
Current Knowledge of θ_{13}

Direct search



allowed region

Global fit



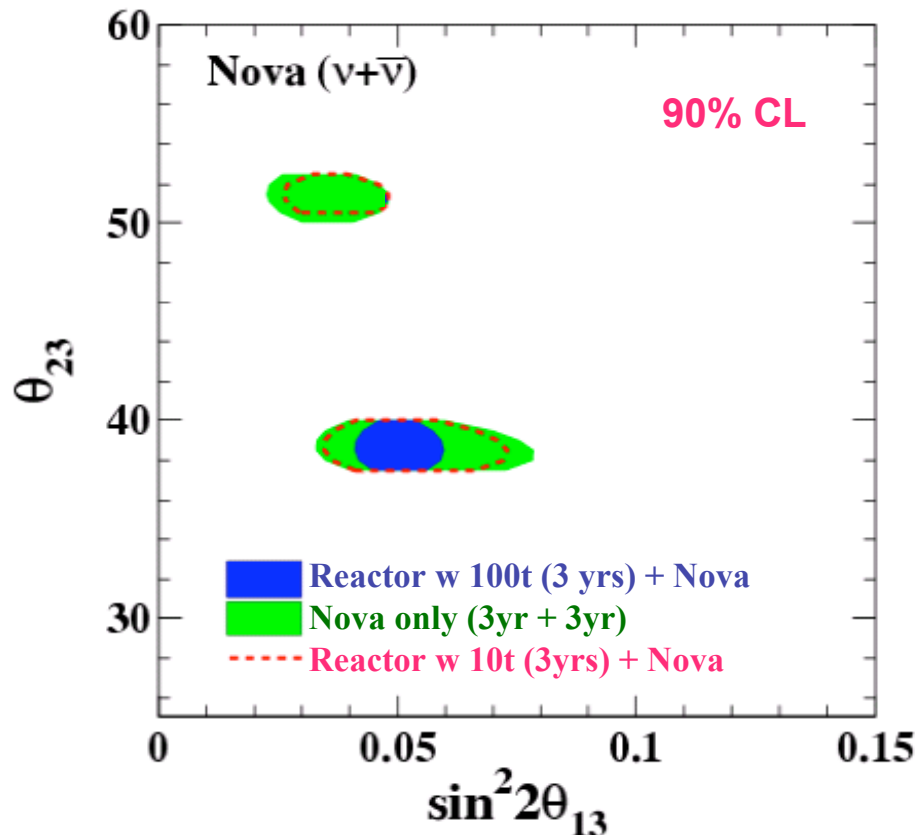
Best fit value of $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV²

Fogli et al., hep-ph/0506083

Synergy of Reactor and Accelerator Experiments

- **Neutrino Scientific Assessment Group:**

the reactor determination of $\sin^2 2\theta_{13}$ helps disentangle the combination of parameters measured by an accelerator ν_e appearance experiment by eliminating some of the ambiguities. A reactor experiment is therefore valuable regardless of its timing with respect to an accelerator experiment.



(Example: $\sin^2 2\theta_{23} = 0.95 \pm 0.01$)

McConnel & Shaevitz, hep-ex/0409028

Recommendations

- **APS Neutrino Study Group:**

- *An expeditiously deployed multidetector reactor experiment with sensitivity to $\bar{\nu}_e$ disappearance down to $\sin^2 2\theta_{13} = 0.01$, an order of magnitude below present limits.*

Our recommendations encourage international cooperation, in order to leverage U.S. investment.

The Neutrino Matrix

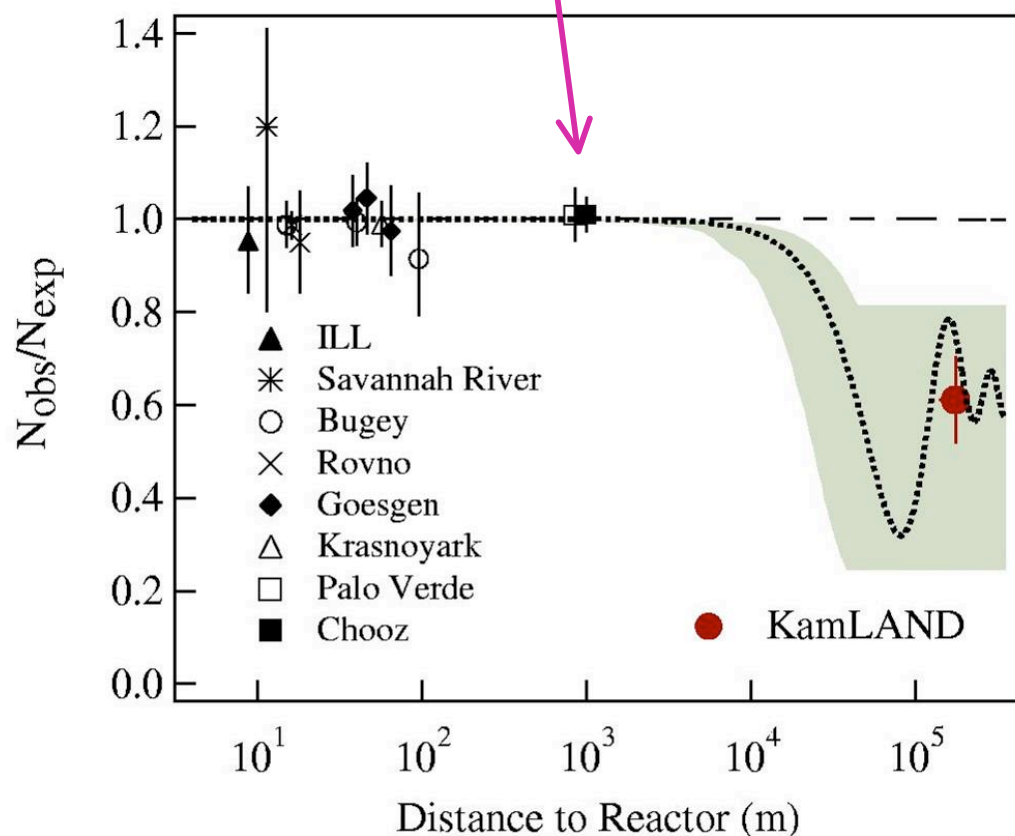
DMP / DPF / DAP / DPE JOINT STUDY ON THE FUTURE OF NEUTRINO PHYSICS

- **Neutrino Scientific Assessment Group:**

The United States should mount one multi-detector reactor experiment sensitive to $\bar{\nu}_e$ disappearance down to $\sin^2 2\theta_{13} \sim 0.01$.

Limitations of Past and Current Reactor Neutrino Experiments

Palo Verde, CHOOZ



Typical precision is 3-6% due to

- limited statistics
- reactor-related systematic errors:
 - energy spectrum of $\bar{\nu}_e$ ($\sim 2\%$)
 - time variation of fuel composition ($\sim 1\%$)
- detector-related systematic error (1-2%)
- background-related error (1-2%)

How To Reach A Precision of 0.01 ?

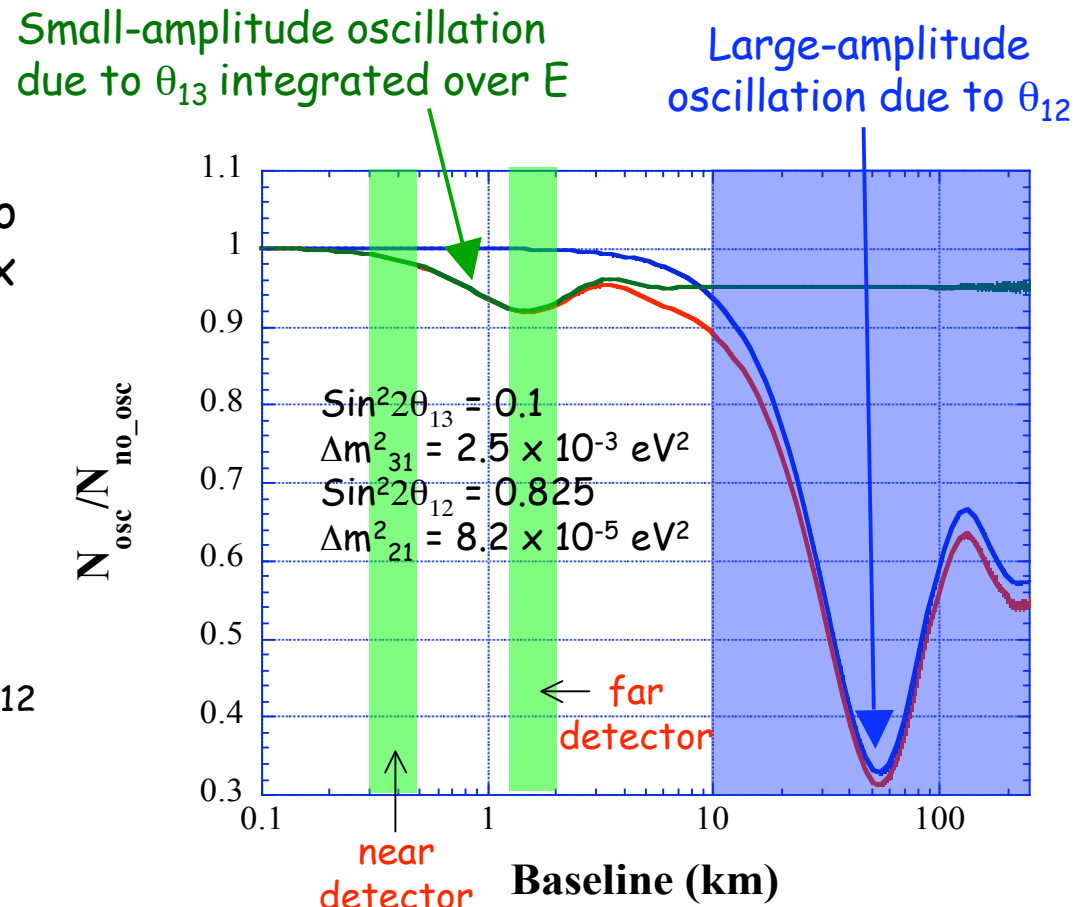
- Powerful nuclear plant
- Larger detectors
- “Identical” detectors
- Near and far detectors to minimize reactor-related errors
- Optimize baseline for best sensitivity and smaller residual reactor-related errors
- Interchange near and far detectors - cancel detector systematic errors
- Sufficient overburden/shielding to reduce background
- Comprehensive calibration/monitoring of detectors

Where To Place The Detectors ?

- Since reactor $\bar{\nu}_e$ are low-energy, it is a disappearance experiment:

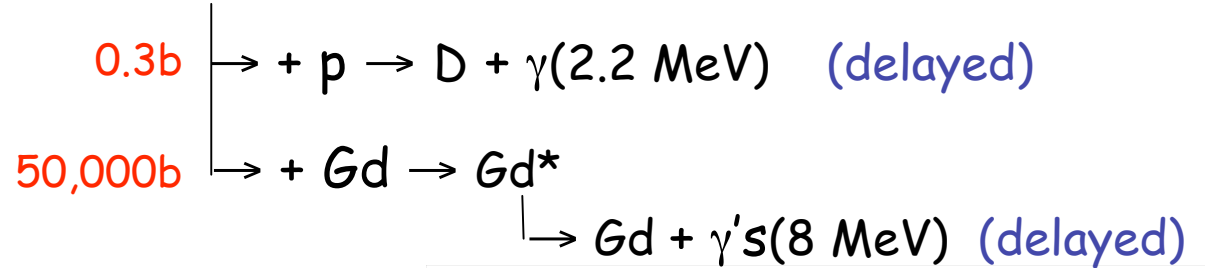
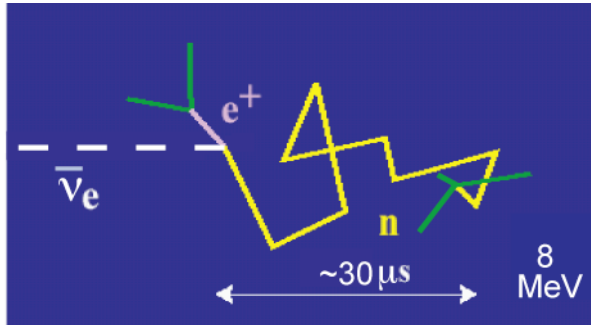
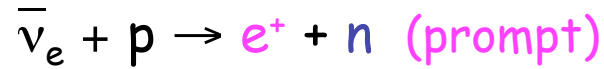
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E} \right)$$

- Place **near detector**(s) close to reactor(s) to measure raw flux and spectrum of $\bar{\nu}_e$, reducing reactor-related systematic
- Position a **far detector** near the first oscillation maximum to get the highest sensitivity, and also be less affected by θ_{12}



Detecting Low-energy $\bar{\nu}_e$

- The reaction is the **inverse β -decay** in 0.1% Gd-doped liquid scintillator:

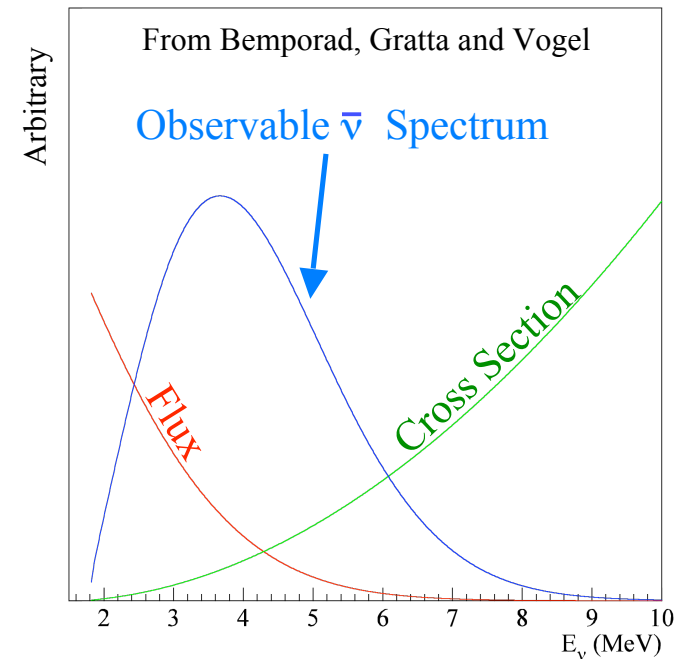


- Time- and energy-tagged signal is a good tool to suppress background events.**

- Energy of $\bar{\nu}_e$ is given by:

$$E_{\bar{\nu}} \approx T_{e^+} + T_n + (m_n - m_p) + m_{e^+} \approx T_{e^+} + 1.8 \text{ MeV}$$

10-40 keV



The Daya Bay Collaboration: China-Russia-U.S.

20 institutions, 89 collaborators

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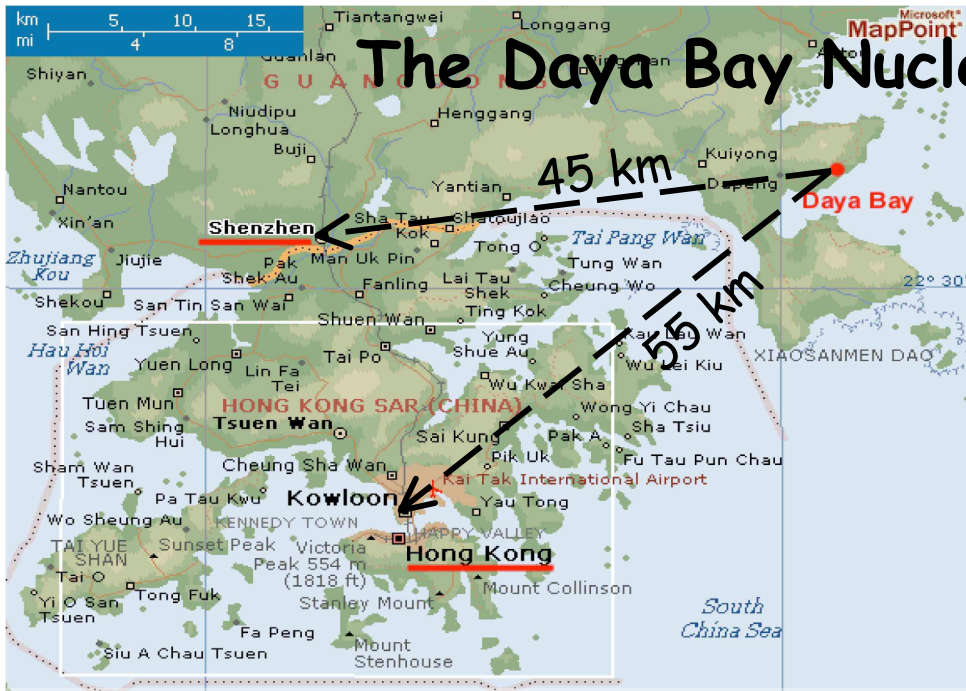
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Daya Bay: Goals And Approach

- Utilize the Daya Bay nuclear power facilities to:
 - determine $\sin^2 2\theta_{13}$ with a sensitivity of 0.01
 - constrain Δm^2_{31}
- Adopt horizontal-access-tunnel scheme:
 - mature and relatively inexpensive technology
 - **flexible** in choosing **overburden** and changing **baseline**
 - relatively easy and cheap to add experimental halls
 - easy access to underground experimental facilities
 - easy to move detectors between different locations with **good environmental control**.
- Employ three-zone antineutrino detectors.



The Daya Bay Nuclear Power Facilities

Ling Ao II NPP:
 $2 \times 2.9 \text{ GW}_{\text{th}}$

Ling Ao NPP:
 $2 \times 2.9 \text{ GW}_{\text{th}}$

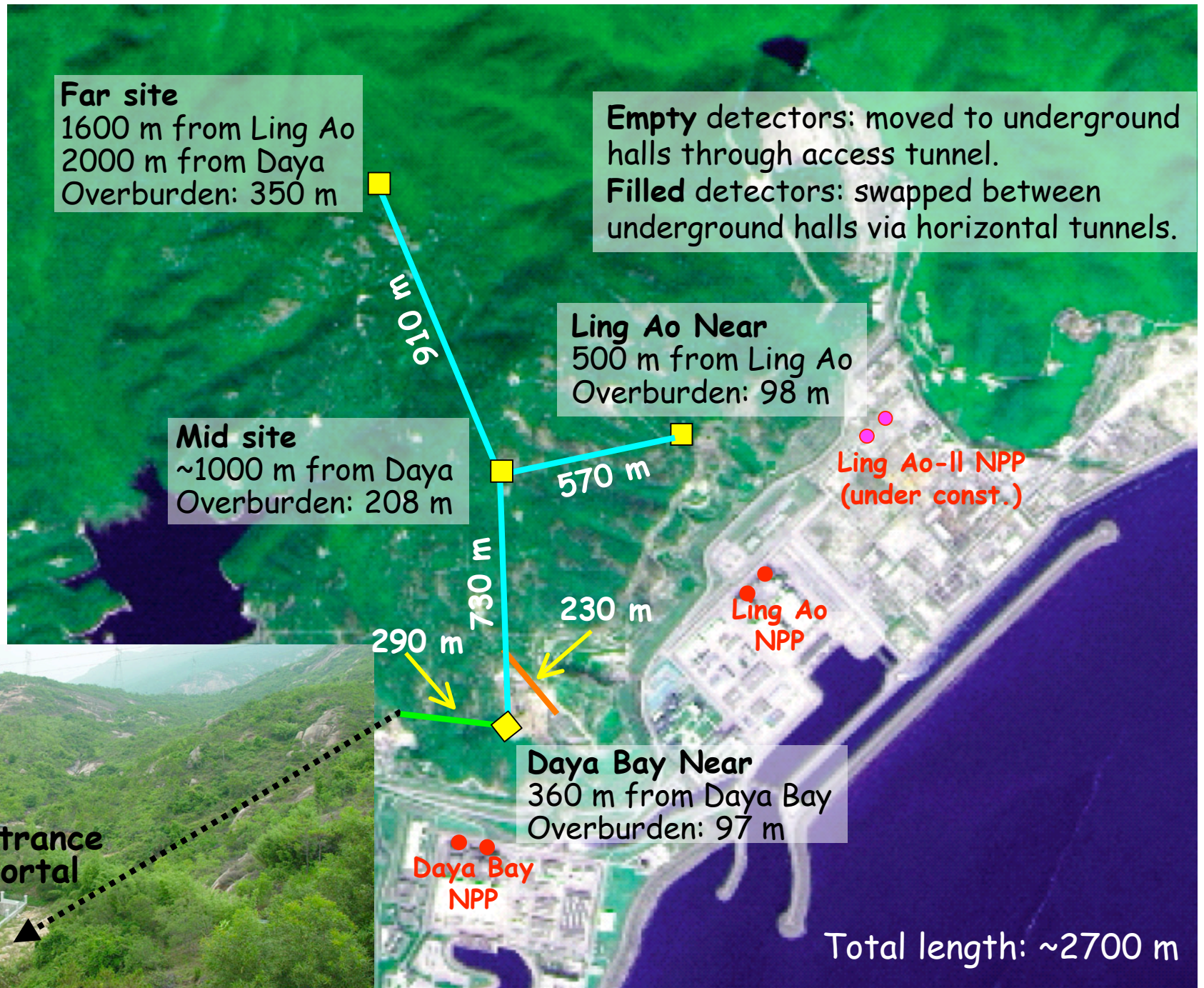
Ready by 2010-2011

1 GW_{th} generates $2 \times 10^{20} \bar{\nu}_e$ per sec

- 12th most powerful in the world (11.6 GW)
- Top five most powerful by 2011 (17.4 GW)
- Adjacent to mountain, easy to construct tunnels to reach underground labs with sufficient overburden to suppress cosmic rays



Daya Bay NPP:
 $2 \times 2.9 \text{ GW}_{\text{th}}$



A Versatile Site

- **Rapid deployment:**
 - Daya Bay near site + mid site
 - 0.7% reactor systematic error



- **Full operation:**

(A) Two near sites + Far site

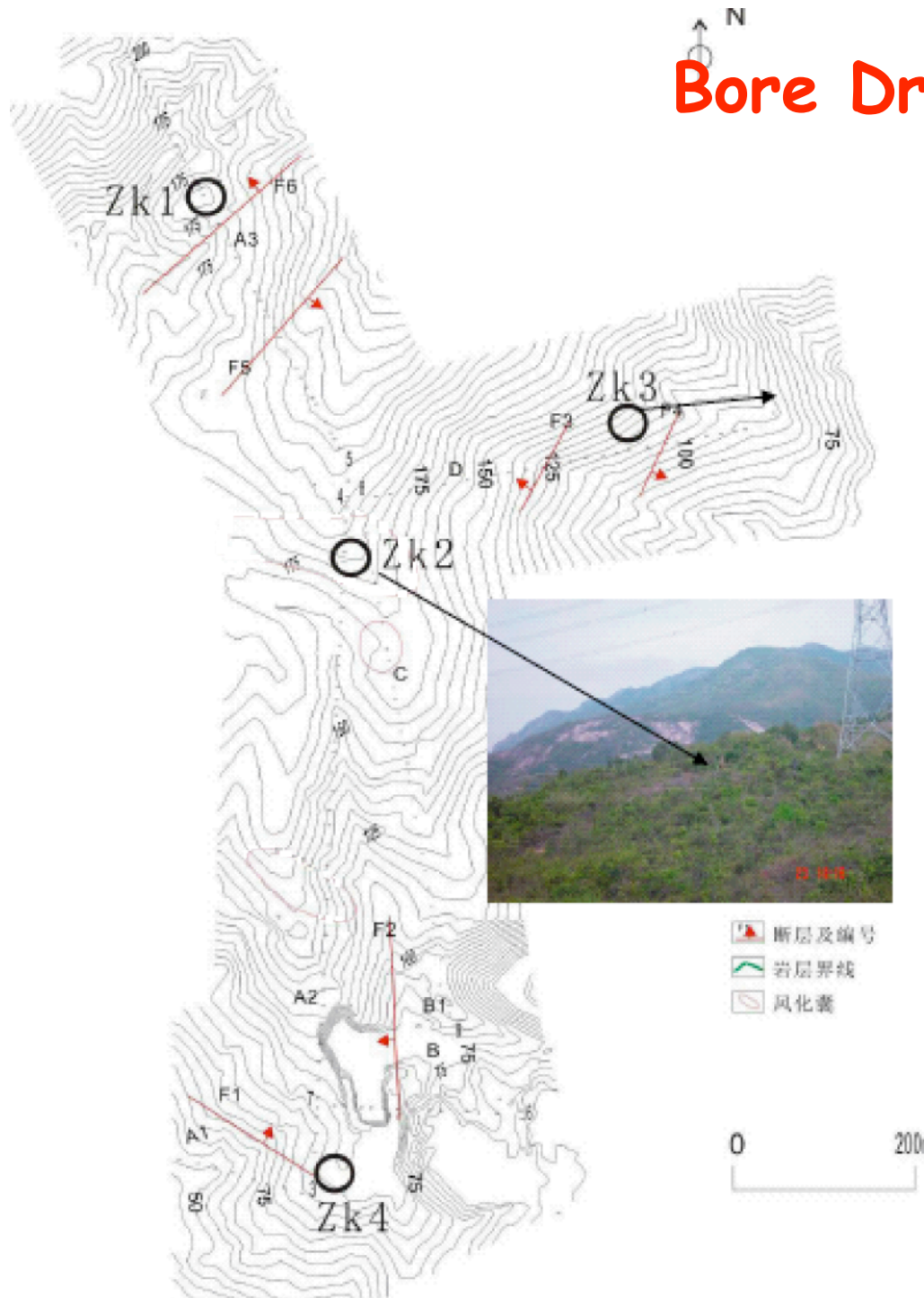
(B) Mid site + Far site

(C) Two near sites + Mid site + Far site

Internal checks, each with different systematic



Bore Drilling



Location	Drill Depth (m)
ZK1	211
ZK2	210
Zk3	127
Zk4	133



Bore Samples

Zk4 (depth: 133 m)



Zk2 (depth: ~180 m)



Zk1 (depth: 210 m)



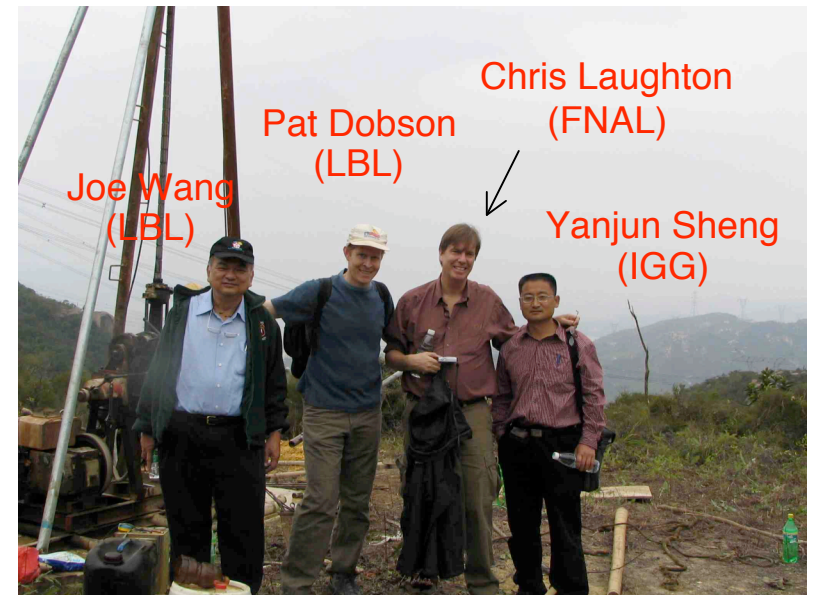
Zk3 (depth: ~64 m)



Findings of Geotechnical Survey

- No active or large faults
- Rock structure: massive and blocky granite
- Rock: most is slightly weathered or fresh
- Groundwater: low flow at the depth of the tunnel
- Quality of rock mass: stable and hard

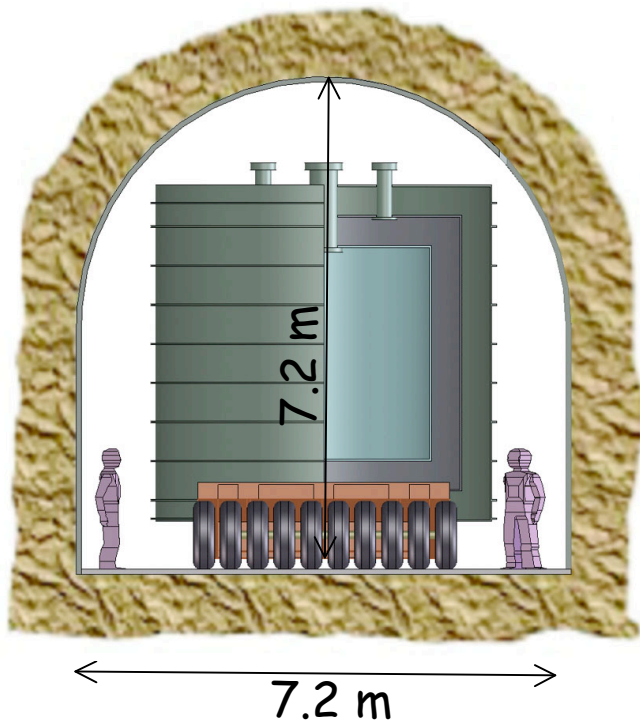
U.S. experts in geology and tunnel construction assist geotechnical survey:



Excellent conditions for tunnel construction

Civil construction

- The total tunnel length is ~3 km
- Preliminary civil construction cost: ~\$3K/m
- Time for tunnel construction is <24 months (>5 m/day)
- A similar tunnel exists on the reactor site as a reference



Design of Antineutrino Detectors

- Three-zone structure:

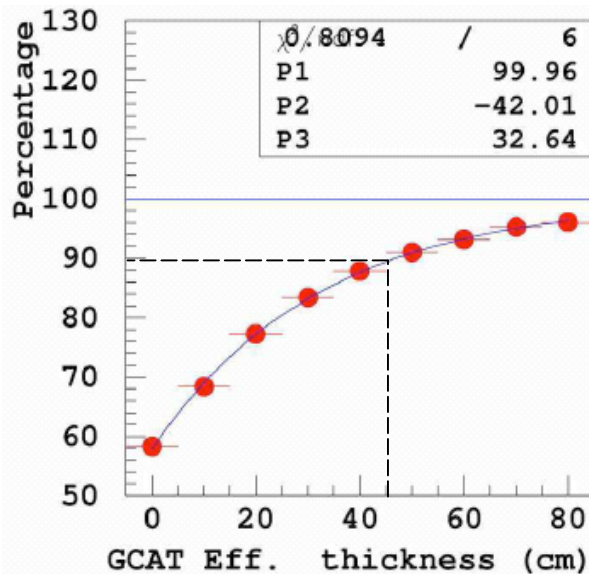
I. Target: 0.1% Gd-loaded liquid scintillator

II. Gamma catcher: liquid scintillator, 45cm

III. Buffer shielding: mineral oil, ~45cm

- Possibly with diffuse reflection at ends. For 200 PMT's around the barrel:

$$\frac{\sigma}{E} \sim \frac{14\%}{\sqrt{E(\text{MeV})}}, \quad \sigma_{\text{vertex}} = 14\text{cm}$$

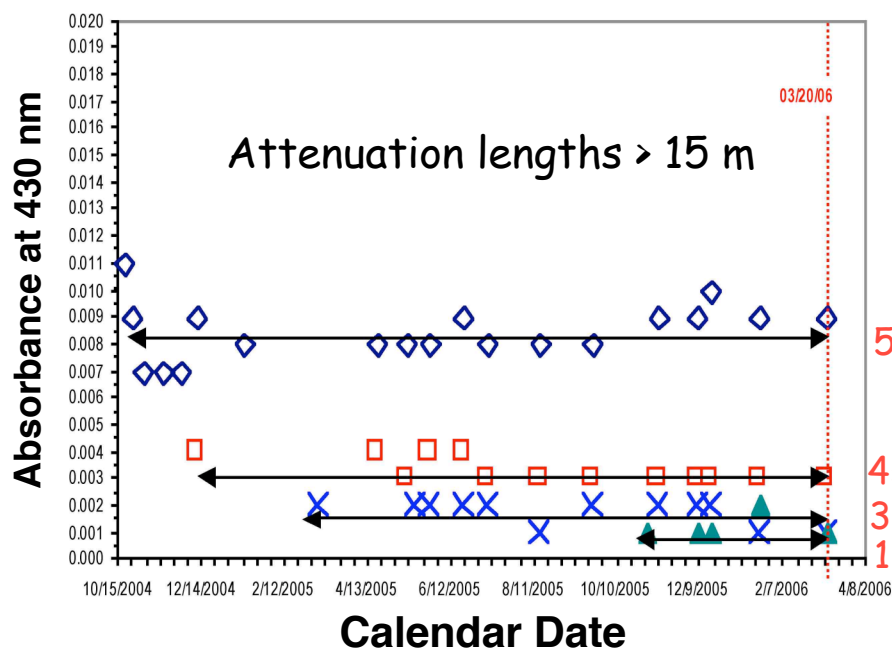


Oil buffer thickness

Isotopes (from PMT)	Purity (ppb)	20cm (Hz)	25cm (Hz)	30cm (Hz)	40cm (Hz)
$^{238}\text{U}(>1\text{MeV})$	50	2.7	2.0	1.4	0.8
$^{232}\text{Th}(>1\text{MeV})$	50	1.2	0.9	0.7	0.4
$^{40}\text{K}(>1\text{MeV})$	10	1.8	1.3	0.9	0.5
Total		5.7	4.2	3.0	1.7

Gd-loaded Liquid Scintillator For Daya Bay

- Require stable Gd-loaded liquid scintillator with
 - high light yield
 - long attenuation length
- BNL nuclear chemists with extensive experience in metal-loaded liquid scintillator have prepared several Gd-doped liquid scintillators with ~1% Gd that can be diluted to ~0.1% Gd for Daya Bay:
 - technology of 1% Gd in pseudocumene (PC) and in mixture of PC and dodecane is mature
 - need R&D for 1% Gd in linear alkyl benzene (LAB)



507 days (1.2% Gd in PC)

455 days (0.2% Gd in PC)

367 days (0.2% Gd in 20% PC + 80% C₁₂H₂₆)

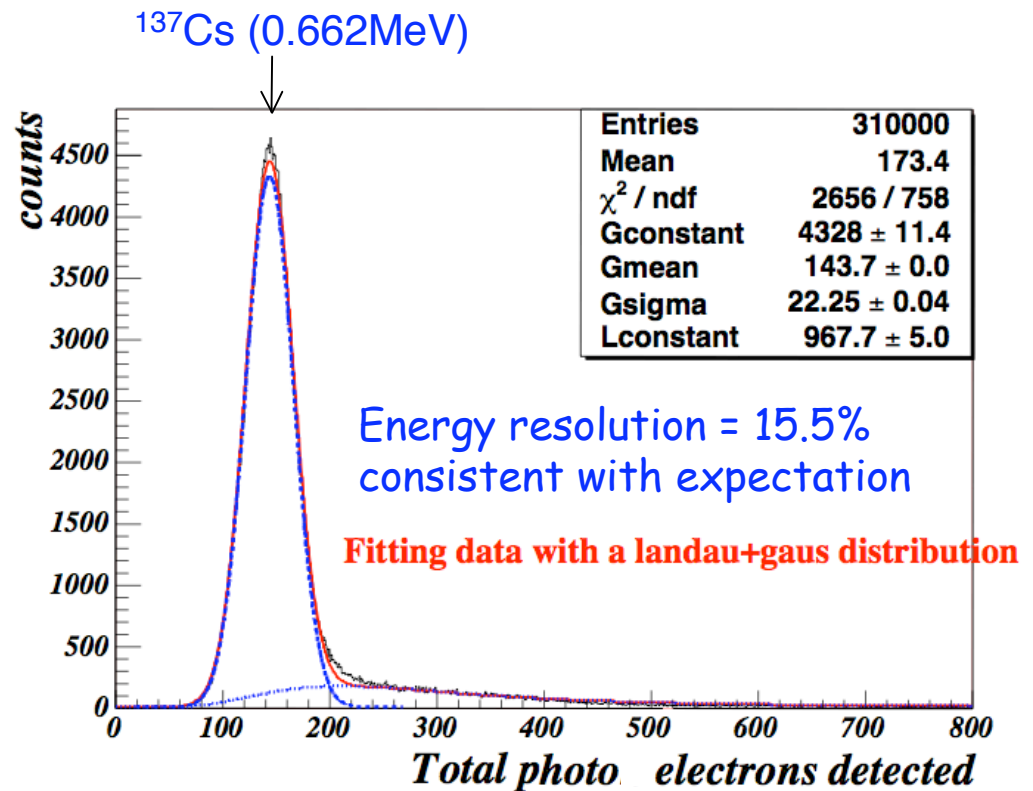
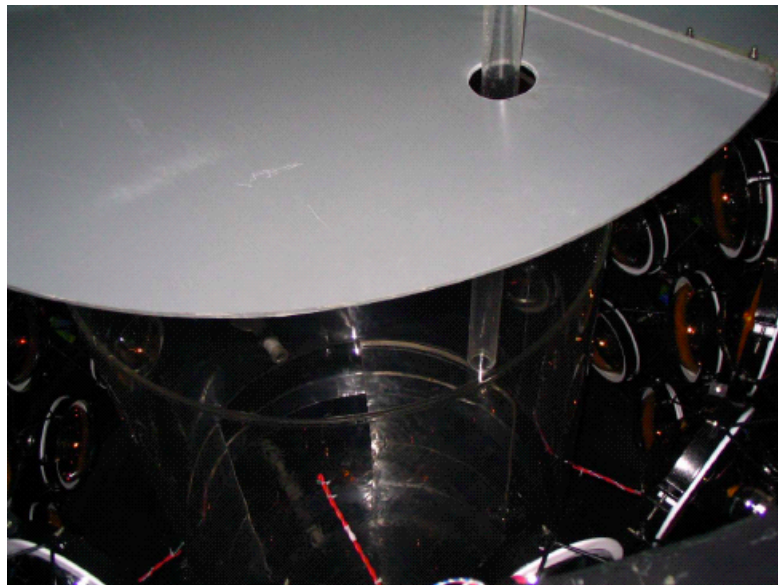
130 days (0.2% Gd in LAB)

- IHEP has also developed good quality Gd-loaded LS.



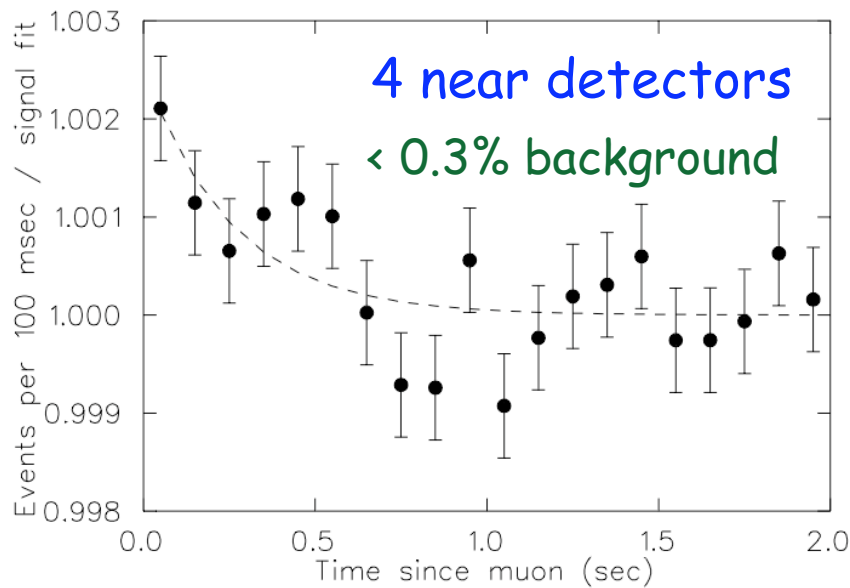
Prototype at IHEP

- Built a 2-zone prototype with reflective surfaces at the top & bottom, 0.5 t (Gd-doped) LS enclosed in 5 t of mineral oil, and 40 8" PMTs to evaluate some design issues at IHEP, Beijing



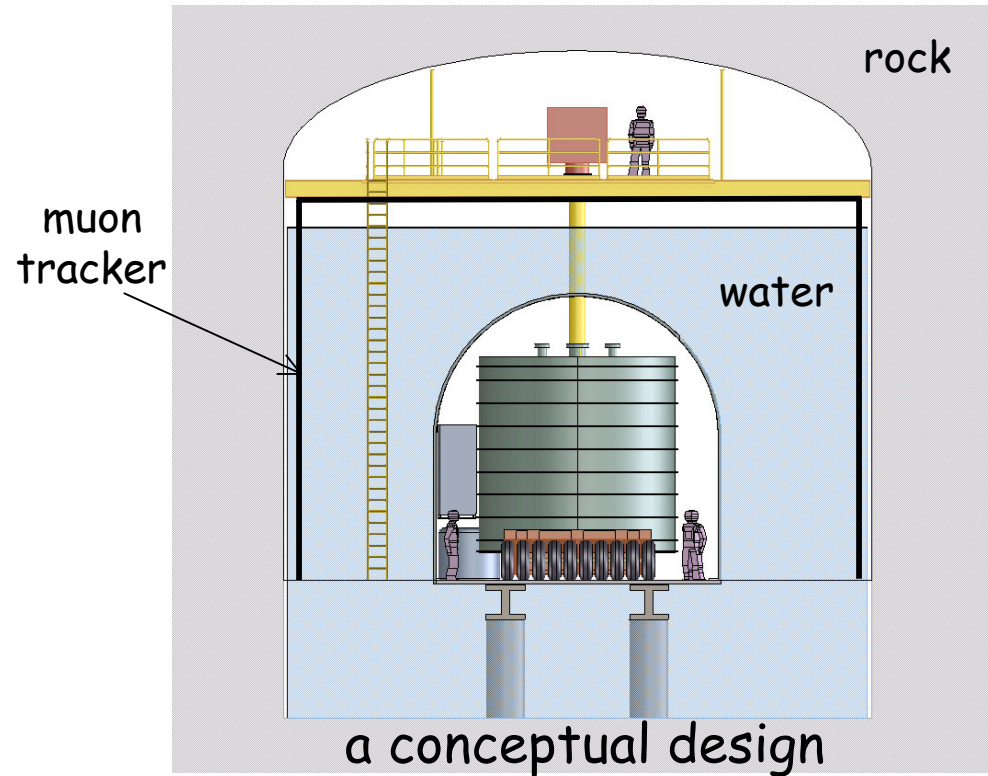
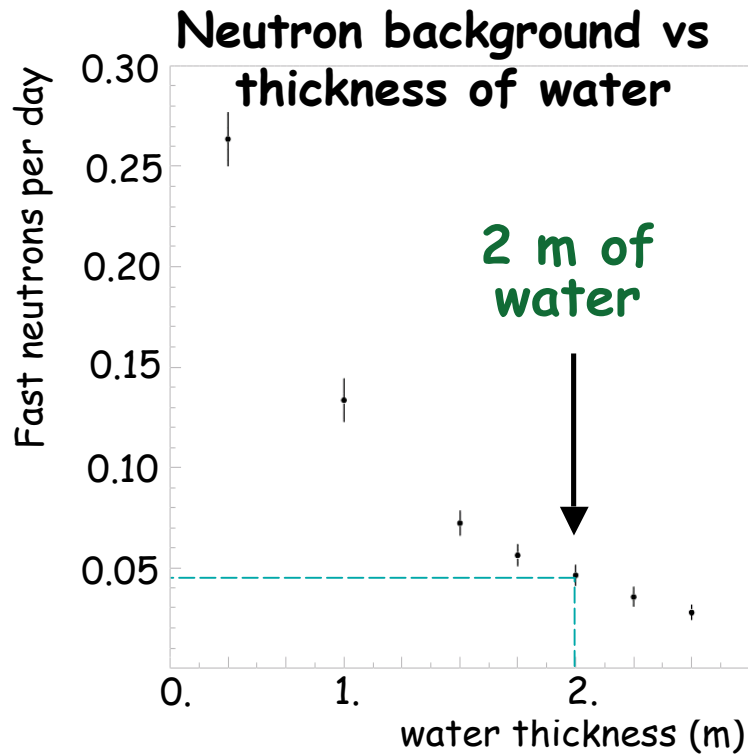
Background

- **Natural Radioactivity:** PMT glass, Rock, Radon in the air, etc
- **Slow and fast neutrons produced by cosmic muons**
 - Neutrons produced in rock
- **Muon-induced cosmogenic isotopes:** $^8\text{He}/^9\text{Li}$ which can β -n decay
 - Cross section measured at CERN (Hagner et. al.)
 - Can be measured in-situ, even for near detectors with muon rate ~ 10 Hz:



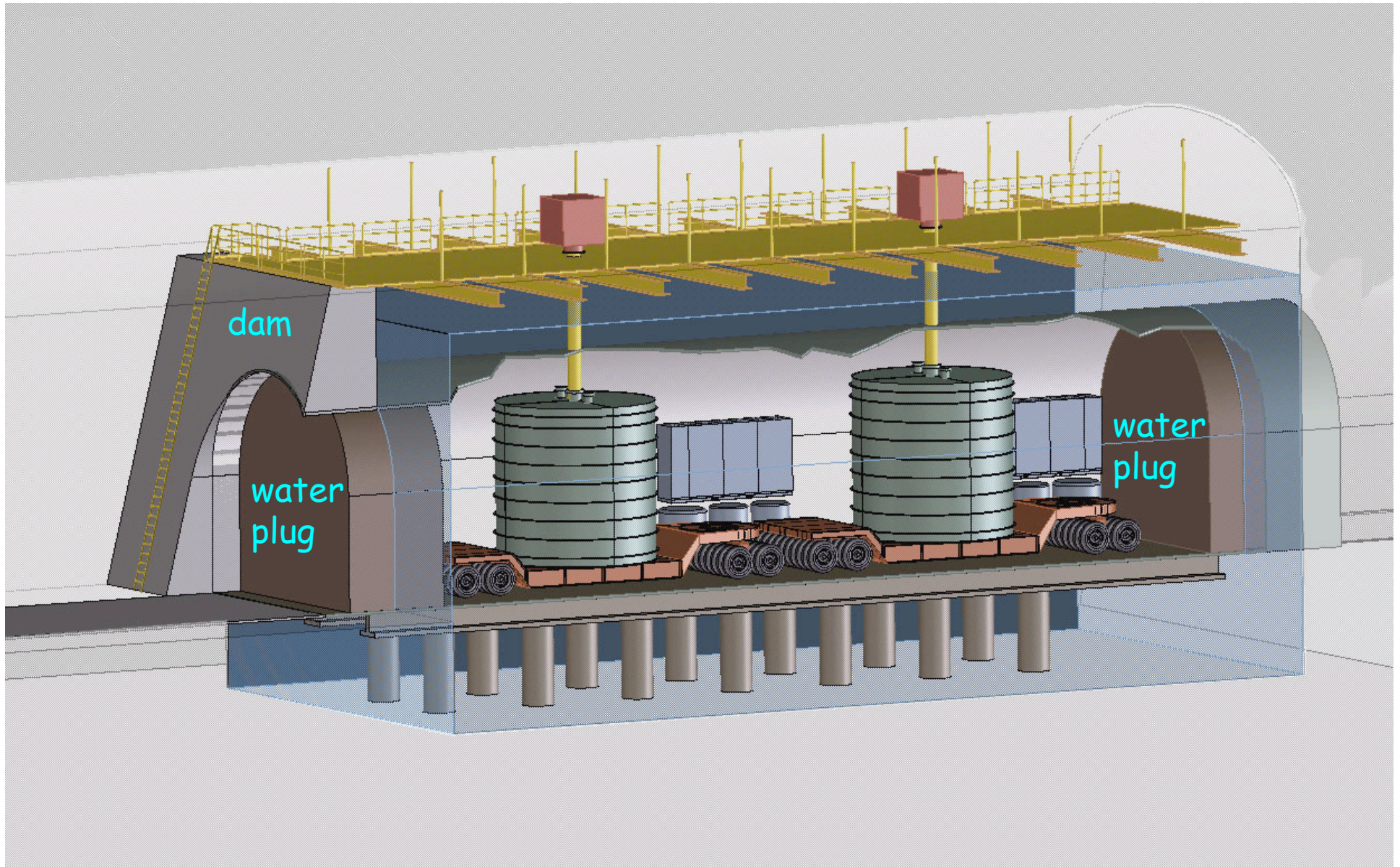
Half-life of $^9\text{Li} = 0.18\text{s}$
 β -n decay of ^9Li mimics signal

Design of Shield-Muon Veto



- Detector modules enclosed by 2 m of water to shield neutrons produced by cosmic-ray muons and gamma-rays from the surrounding rock
- Water shield also serves as a Cherenkov veto for tagging muons
- Augmented with a muon tracker: scintillator or RPCs
- Combined efficiency of Cherenkov and tracker $> 99.5\%$

Underground Experimental Hall



Summary of Background

- Use a modified Palo Verde-Geant3-based MC to model response of detector:

	Near Site	Far Site
Radioactivity (Hz)	<50	<50
Accidental B/S	<0.05%	<0.05%
Fast neutron B/S	$0.14\% \pm 0.16\%$	$0.08 \pm 0.1\%$
$^8\text{He}/^9\text{Li}$ B/S	$0.41\% \pm 0.18\%$	$0.2\% \pm 0.08\%$

Further rejection of background may be possible by cutting showering muons.

The Aberdeen Tunnel Experiment

- Study cosmic muons & cosmogenic background in Aberdeen Tunnel, Hong Kong.

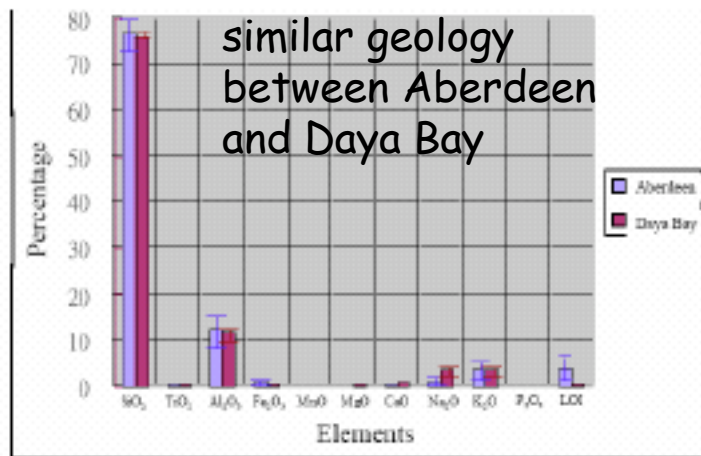
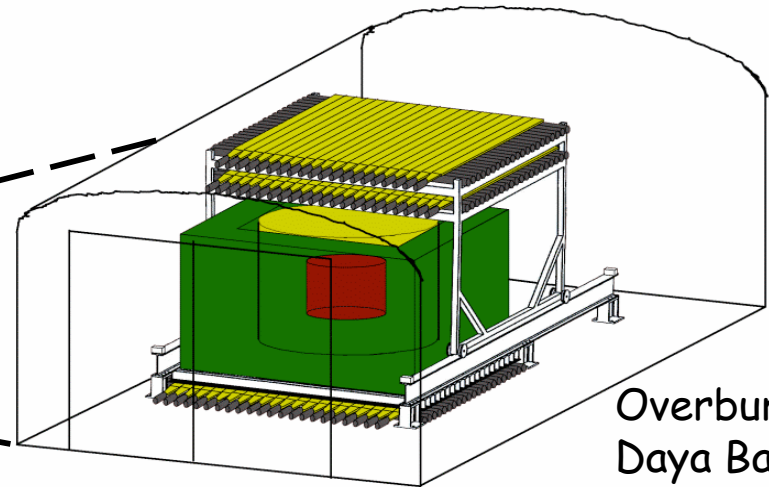


Fig. 1 A comparison of rock compositions at Daya Bay and Aberdeen.

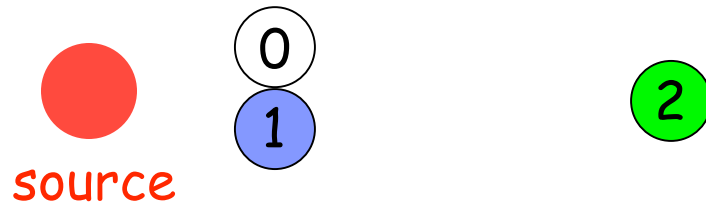


Systematic Uncertainty

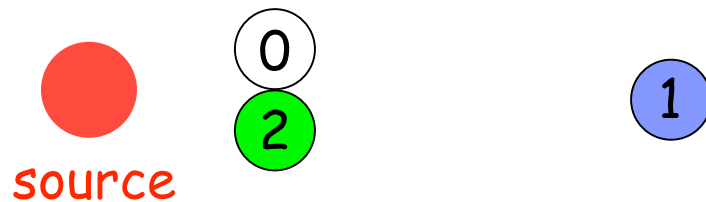
- Main contributions:
 1. Reactor-related errors
 2. Detector-related errors
- Swapping detectors can reduce detector systematic errors
- Assume background is measured

Detector Swapping

Basic concept:



Detector 0 is used to cross check detectors before and after swapping



$$\frac{N_1}{F_2} = \frac{N}{F} \cdot \frac{\varepsilon_1}{\varepsilon_2}$$

N = number of $\bar{\nu}$ at near site

ε_1 = efficiency of detector 1

F = number of $\bar{\nu}$ at far site

ε_2 = efficiency of detector 2

$$\frac{N_2}{F_1} = \frac{N}{F} \cdot \frac{\varepsilon_2}{\varepsilon_1} = \frac{N}{F} \left(1 + \frac{\delta}{\varepsilon_1} \right)$$

$$\frac{N_1}{F_2} + \frac{N_2}{F_1} \approx 2 \frac{N}{F} \left[1 + \frac{1}{2} \left(\frac{\delta}{\varepsilon_1} \right)^2 \right] = 2 \frac{N}{F} (1 + \eta)$$

For example,

$\varepsilon_1 \approx 0.8$ (KamLAND)

$\delta = 0.02$

$\Rightarrow \eta = 3 \times 10^{-4}$

Reactor-related Uncertainties of Daya Bay

- The error due to power fluctuations of the reactors is given by:

$$\sigma_{sys} = \sigma_p \sqrt{\sum_r \left(f_F^r - f_N^r\right)^2}$$

Based on experience of past experiments, due to uncertainty in measuring the amount of thermal power produced, the uncorrelated error per reactor core $\sigma_p \approx 2\%$.

f_F^r and f_N^r are fractions of the events at the far and near site from reactor r respectively.

# Reactor Cores	Syst. error due to Power Fluctuations	Syst. error due to Core Positions	Total syst. error
4	0.035%	0.08%	0.087%
6	0.097%	0.08%	0.126%

Detector-related Uncertainties

Source of error		Absolute measurement	Relative measurement		
		CHOOZ	Daya Bay Baseline	Goal	w/ Swapping
# protons	H/C ratio	0.8	0.2	0.1	→ 0
	Mass	-	0.2	0.02	→ 0.006
Detector Efficiency	Energy cuts	0.8	0.2	0.05	
	Position cuts	0.32	0.0	0.0	
	Time cuts	0.4	0.1	0.03	
	H/Gd ratio	1.0	0.01	0.01	→ 0
	n multiplicity	0.5	0.05	0.01	
	Trigger	0	0.01	0.01	
	Live time	0	< 0.01	< 0.01	
Total detector-related uncertainty		1.7%	0.36%	0.12%	→ 0.06%

Baseline: currently achievable **relative** uncertainty without R&D

Goal: expected **relative** uncertainty after R&D

Swapping: can reduce **relative** uncertainty further

Summary of Systematic Errors

- Reactor-related systematic errors are:

0.09% (4 cores)

0.13% (6 cores)

- Relative detector systematic errors are:

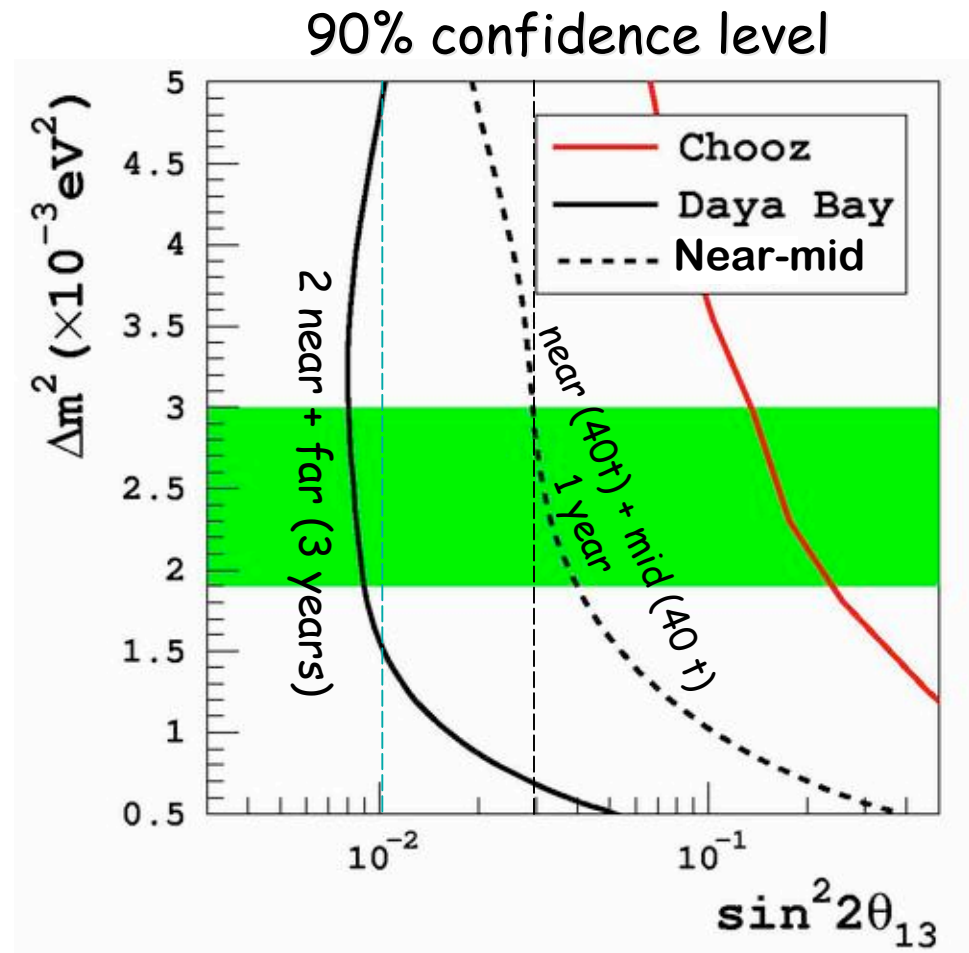
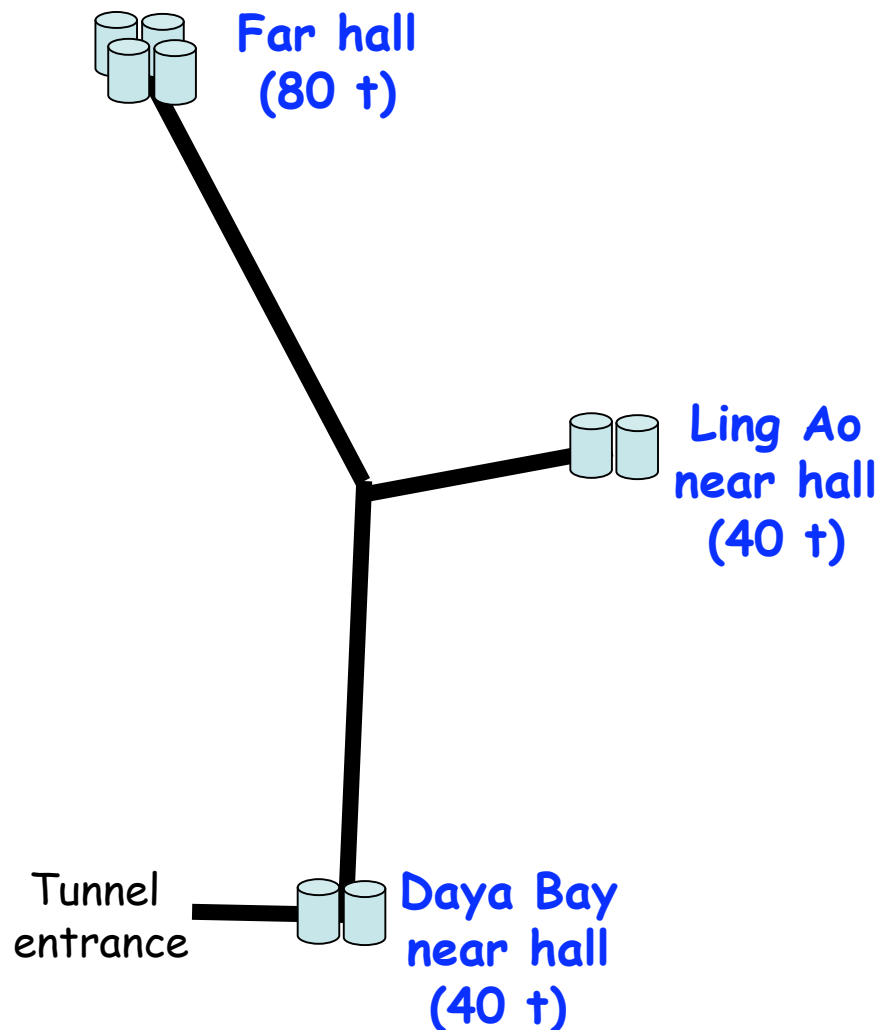
0.36% (baseline)

0.12% (goal)

0.06% (with swapping)

- These are input to sensitivity calculations

Sensitivity of Daya Bay in $\sin^2 2\theta_{13}$



- Use rate and spectral shape
- input relative detector systematic error of 0.2%

Current Scope & Responsibility List by Country

WBS	Description	Majority Responsibility	
		China	US
1	Central Detector	✓	
	System design, steel vessels, unloaded LS, mineral oil,	✓	
	readout electronics co-design, electronics mfg, safety	✓	
	systems, racks, assembly & installation	✓	
	Acrylic vessels, PMT's & support structure, Gd loaded LS,		✓
	LS purification system, locomotion system, readout		✓
	electronics co-design, cables, crates		✓
2	Veto Detector		✓
	System design, muon tracker system, supplemental water		✓
	veto PMT's, muon tracker assy & test		✓
	Water veto system hardware, compensation coils, readout	✓	
	electronics mfg, safety syst, water veto assy & test	✓	
3	Calibration & Monitoring Systems		✓
	Automated deployment system & glove box, laser sources,		✓
	monitoring system & system test		✓
	Manual calibration sys & glovebox, LED sources, radioactive	✓	
	calib. sources, low-background source & matls counting syst	✓	

Scope & Responsibility List - Continued

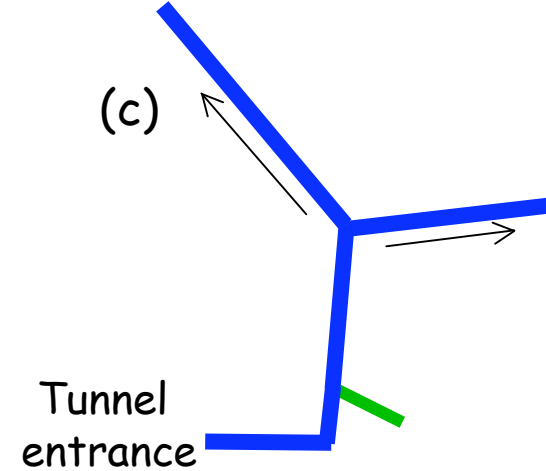
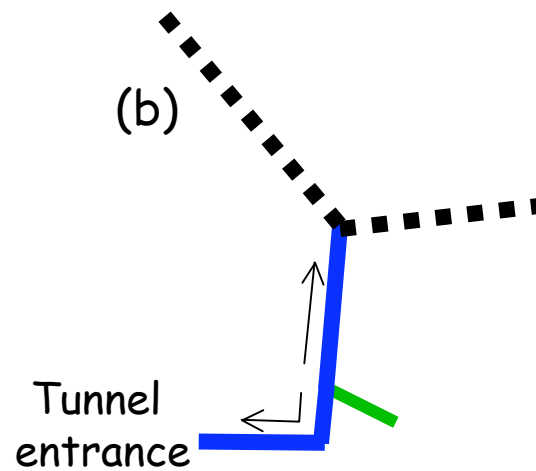
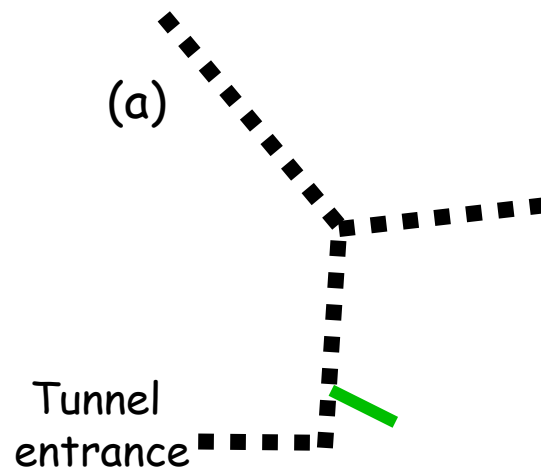
WBS	Description	Majority Responsibility	
		China	US
4	DAQ, Trigger, Online & Offline Hardware	✓	
	DAQ & trigger board co-design, board manufacture, racks,	✓	
	monitoring & controls hardware, some on-line hardware	✓	
	DAQ & trigger board co-design, crates, cables, on-line hardware		✓
	off-line hardware & data archiving in US, system test platform		✓
5	DAQ, Trigger, Online & Offline Software	✓	✓
	Overall software architecture, DAQ & trigger software,	shared	shared
	on-line & off-line software, simulations software	shared	shared
	Monitoring & controls software	✓	
6	Conventional Construction & Equipment	✓	
	Tunnels, entrances, experimental halls, underground utilities,	✓	
	safety systems, surface facilities	✓	
7	System Integration	✓	✓
8	Project Management	✓	✓

- Russia will contribute to liquid scintillator, calibration, and plastic scintillator
- Taiwan will contribute to the acrylic vessels and trigger electronics
- Hong Kong will contribute to calibration and data storage

Major Items of U.S. Project Scope

- Muon tracking system (veto system)
- Gd-loaded liquid scintillator
- Calibration systems
- PMT's, base's & control
- Design readout & trigger electronics
- Acrylic vessels (antineutrino detector)
- Other mechanical components
- Detector integration activities
- Project management activities

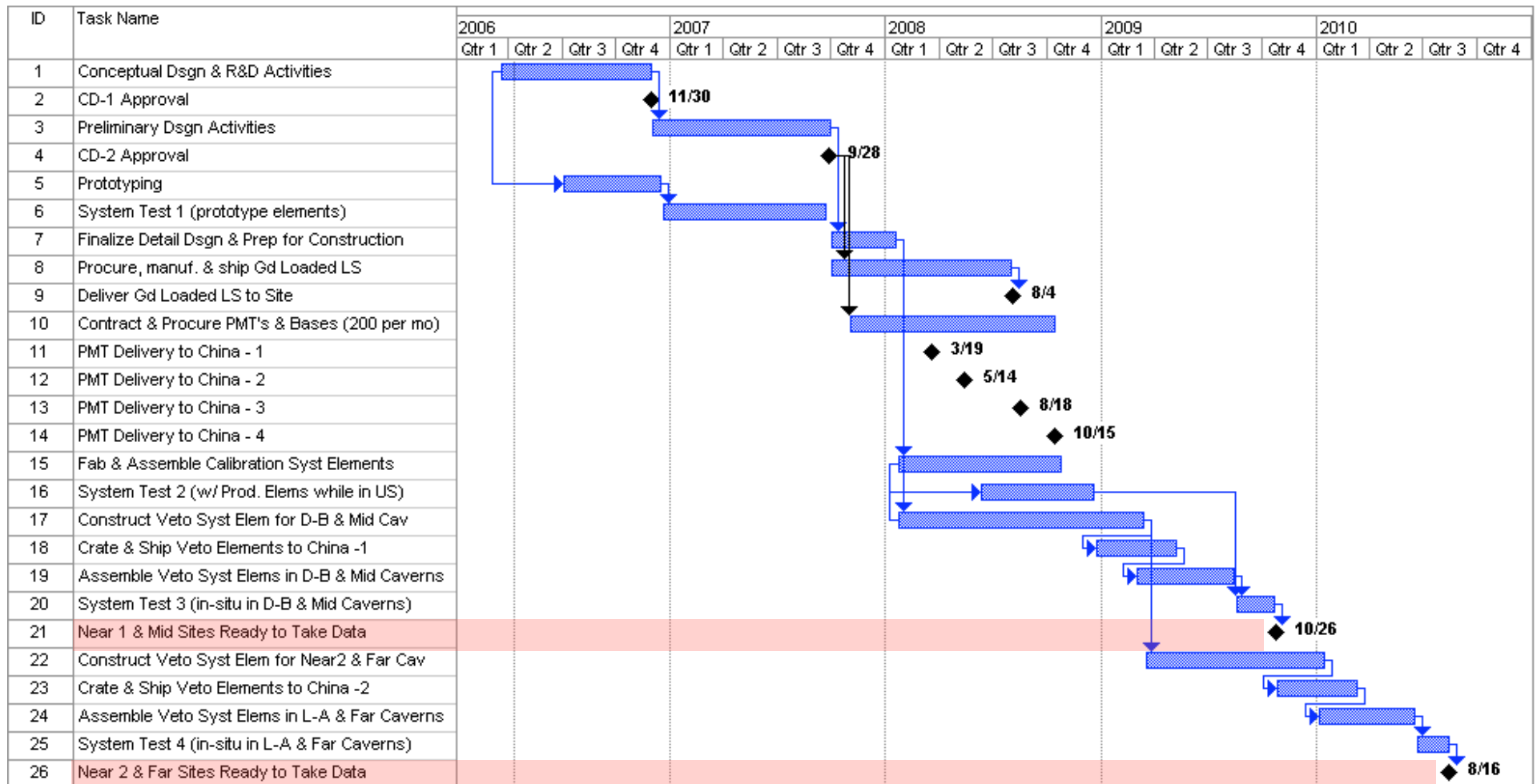
Prelim. Civil Construction Schedule



Based on preliminary study of civil construction by BINE in China

ID	Task Name	Duration	Start	2006				2007				2008				2009
				Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1
1	Establish Prelim Specs for Civil Dsgn	65 days	Fri 3/17/06													
2	Civil Design of tunnels & caverns	140 days	Fri 6/16/06													
3	Select Civil Construction Firm	45 days	Fri 12/29/06													
4	Mobilize Equipment & prep for constr.	50 days	Fri 3/2/07													
5	Construct 200m waste removal tunnel	40 days	Fri 5/11/07													
6	Tunnel to DayaBay Entr & Mid site (500m ea)	100 days	Fri 7/6/07													
7	Construct D-B Near Hall & Mid Hall in Parallel	70 days	Fri 11/23/07													
8	Install Utilites in D-B Near & Mid Hall in Parallel	80 days	Fri 2/29/08													
9	D-B Near & Mid Halls Complete - Ready for Instal	1 day	Fri 6/20/08													
10	Cont. Tunnel to L-A Near (700m) & Far Site (1000m)	135 days	Fri 11/23/07													
11	Constuct Ling-Ao Near Hall	70 days	Fri 5/30/08													
12	Construct Far Site Hall	90 days	Fri 5/30/08													
13	Install Utilites in L-A Near & Far Hall in Parallel	80 days	Fri 9/5/08													
14	L-A Near & Far Halls Complete - Ready for Instal.	1 day	Fri 12/26/08													

Prelim. Overall Project Schedule



Project Development

- Schedule/activities over next several months:

Determine scale of detector for sizing halls: now - June

Continue building strong U.S. team - key people: now - summer

Conceptual design, scale & technology choices: now - Aug

Firm up U.S. scope, schedule & cost range: July - Nov

Write CDR, prepare for CD-1 review: Aug - Nov

Funding Profile

FY08	U.S. Construction	\$10M
FY09		\$14M
FY10		\$ 8M

CD-1 review in U.S.

November 2006

Begin construction in China

March 2007

CD-2 review in U.S.

September 2007

Begin data collection

January 2010

Measure $\sin^2 2\theta_{13}$ to ≤ 0.01

March 2013

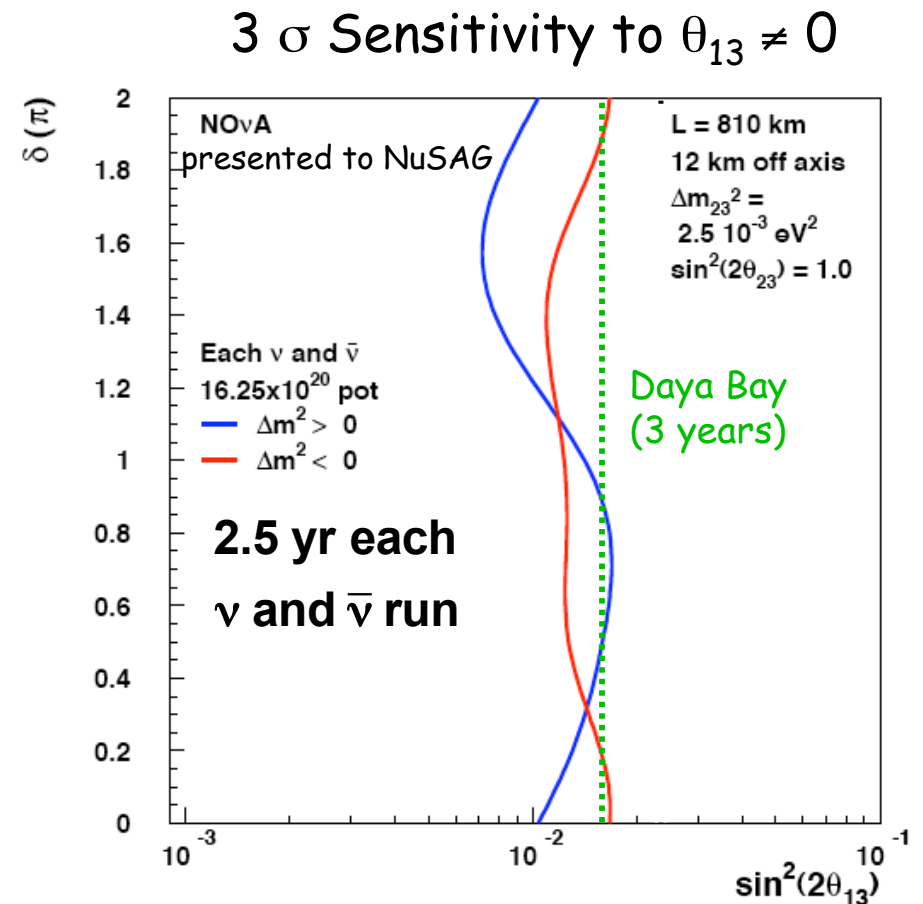
Synergy Between Reactor and Accelerator Experiments

Before 2011:

Daya Bay provides basis for early decision on future program beyond NO ν A for CP and mass hierarchy

After 2011:

Daya Bay will complement NO ν A and T2K for resolving θ_{23} , mass hierarchy, and CP phase



Summary

- The Daya Bay nuclear power facilities in China and the mountainous topology in the vicinity offer an excellent opportunity for carrying out a reactor neutrino program using horizontal tunnels.
- The Daya Bay experiment has excellent potential to reach a sensitivity of ≤ 0.01 for $\sin^2 2\theta_{13}$.
- The Daya Bay Collaboration continues to grow. International working groups with U.S.-China co-leadership have been established.
- Will complete preliminary design of detectors and detailed design of tunnels and underground facilities in 2006.
- Plan to start with the Fast Deployment scheme in 2009, and begin full operation in 2010.